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Neutrino, photon interaction in unparticle physics

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ABSTRACT

We investigate the impact of unparticle physics on the annihilation of relic neutrinos with the neutrinos identified as primary source of ultra high energy (UHE) cosmic ray events, producing a cascade of photons and charged particles. We compute the contribution of the unparticle exchange to the cross-sections $\nu\bar{\nu} \to \gamma\gamma$ and $\nu\bar{\nu} \to f\bar{f}$ scattering. We estimate the neutrino–photon decoupling temperature from the reaction rate of $\nu\bar{\nu} \to \gamma\gamma$. We find that the inclusion of unparticles can in fact account for the flux of UHE cosmic rays and can also result in the lowering of neutrino–photon decoupling temperature below the QCD phase transition for unparticle physics parameters in a certain range. We calculate the mean free path of these high energy neutrinos annihilating themselves with the relic neutrinos to produce vector, axial-vector and tensor unparticles.

1. Introduction

High energy neutrino interactions are of great interest in astrophysics, cosmology and in high energy cosmic ray physics. Neutrinos have been considered as possible candidates of Ultra High Energy (UHE) cosmic rays as opposed to protons and photons on account of their ability to travel cosmic galactic distances without significantly degrading their energy. In comparison to protons and photons, neutrinos have relatively weaker interaction cross-section with relic neutrinos and CMBR. By the same token they present difficulty in initiating air showers. Weiler [1] proposed that if their energy could correspond to Z-resonance, i.e.,

$$E_\nu \approx \frac{m_Z^2}{2m_\nu} \simeq 10^{23}\ \text{eV}, \tag{1}$$

they would have significant annihilation cross-section with relic neutrinos of mass consistent with the oscillation data. The difficulty in realizing this scenario is to identify the source of UHE neutrinos with their energy close to Z-resonance. Decay of super heavy relic particles $M_\chi \geqslant 10^{13}$ GeV has been proposed [2] to be the source of these highly energetic neutrinos that can explain cosmic ray events above the GZK cut off. There however, remains the problem of confining the production of these neutrinos in a spherical shell at red shift

$$Z = \left[\frac{M_\chi}{2\ \text{Eres}} - 1\right] = \left[\frac{M_\chi m_\nu}{m_Z^2} - 1\right], \tag{2}$$

so that this energy near earth is close to Z-resonance energy for the $\nu\bar{\nu}$ annihilation cross-section on relic neutrinos to be large. If such a scenario is not realized in nature, we would require large neutrino-hadron cross-section in the millibarn (mb) region for the neutrinos to initiate showers high in the atmosphere. Current estimate of UHE neutrino–hadron cross-section in the Standard Model (SM) by Gandhi et al. [3] put the cross-section in the 10^{-4}–10^{-5} mb range for $E_\nu \sim 10^{21}$ eV.

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We thus require anomalously large high energy neutrino interactions. In this context theories of n-extra dimensions with large compactification radius and TeV scale gravity [4] provide the possibility of enhancing neutrino interactions through the exchange of a tower of massive spin 2 bulk gravitons (Kaluza–Klein excitations). The contribution of Kaluza–Klein excitations and its impact on UHE cosmic ray physics has been discussed by several authors [5] in the literature.

The high energy neutrino–photon interactions are also of great interest in astrophysics and cosmology. Scattered photons on neutrinos through $\gamma\nu \to \gamma\nu$ are predominantly circularly polarized due to the left handed nature of neutrinos [6]. In the early universe, the photons and neutrinos decouple, i.e., the process $\nu\bar{\nu} \to \gamma\gamma$ ceases to occur at a temperature $T \sim 1.6$ GeV about one micro second after the big bang. If due to some enhanced neutrino–photon interaction, this temperature can be brought down to the QCD phase transition temperature, some remnants of circular polarization could perhaps be retained in the cosmic microwave background. In the SM these cross-sections are very small, due to the vector and axial vector nature of weak interaction and the leading term for massless neutrinos in fact vanishes due to Yang's theorem [7]. The cross section for $\gamma\gamma \to \nu\bar{\nu}$ has been calculated in the SM [8] and shows an s^3 behavior upto $W^{\pm}$ pair production threshold beyond which it starts falling. The cross section is given by

$$\sigma(\nu\bar{\nu} \to \gamma\gamma) = \frac{s^3}{20\pi}\left(\frac{Ag^2\alpha_{\text{em}}}{32\pi m_W^4}\right)^2, \quad \text{where } A = 14.4. \tag{3}$$

The contribution of Kaluza–Klein excitations to these processes has been computed by Dicus et al. [9], who have shown that the contribution is not large enough to allow high energy neutrinos to scatter from relic neutrinos through $\nu\bar{\nu} \to \gamma\gamma$ but photon–neutrino decoupling temperature may in fact be lowered.

Recently Georgi [10,11] has proposed that the scale invariance, which has been a powerful tool in physics, may indeed exist at a scale much above the TeV scale. He argued that at high energies there is a hidden sector with a non-trivial IR fixed point $\Lambda_{\mathcal{U}}$, below which there is a scale invariance. At energies above $\Lambda_{\mathcal{U}}$, there is a hidden sector operator $\mathcal{O}_{\text{UV}}$ of dimension $d_{\mathcal{UV}}$ much like the Banks–Zaks [12] scale invariant sector. This couples to SM operator $\mathcal{O}_{\text{SM}}$ of dimension d_{SM} through the exchange of high mass $M_{\mathcal{U}}$ particles.

$$\mathcal{L}_{\text{eff}} = \frac{\mathcal{O}_{\text{SM}}\mathcal{O}_{\mathcal{UV}}}{M^{d_{\mathcal{U}}+d_{\text{SM}}-4}}. \tag{4}$$

Below $\Lambda_{\mathcal{U}}$, the hidden sector becomes scale invariant and the operator $\mathcal{O}_{\mathcal{UV}}$ goes over to an operator $\mathcal{O}_{\mathcal{U}}$ called an unparticle operator with a non-integral scale dimension $d_{\mathcal{U}}$. The unparticle operator has a mass spectrum which looks like the mass spectrum of $d_{\mathcal{U}}$ number of massless particles. The unparticles have continuous mass spectrum. The unparticle operators can have different Lorentz structures and couple to the SM fields at low energies through an effective non-renormalizable Lagrangian

$$\mathcal{L}_{\mathcal{U}} = \mathcal{C}_{\mathcal{U}}\frac{\Lambda_{\mathcal{U}}^{d_{\mathcal{UV}}-d_{\mathcal{U}}}}{M^{d_{\mathcal{UV}}-d_{\text{SM}}-4}}\mathcal{O}_{\text{SM}}\mathcal{O}_{\mathcal{U}} \tag{5}$$

and $\mathcal{C}_{\mathcal{U}}$ is the dimensionless coupling constant.

This unparticle sector can arise as stated in [10] from the hidden sector or from the strongly interacting magnetic phase of a specific class of supersymmetric theories [13] or from the hidden valleys model [14]. However, we also note that under a specific conformal invariance [15] the propagators for vector and tensor unparticle operators are modified.

In this Letter we study the attenuation of high energy neutrinos through interaction with the present density of relic neutrinos through $\nu\bar{\nu} \to \mathcal{U}$, $\nu\bar{\nu} \to \gamma\gamma$ and $\nu\bar{\nu} \to f\bar{f}$ processes. The last two processes will proceed through the exchange of $\mathcal{U}$ unparticles and would directly produce a cascade of high energy photons and hadrons which could account for the flux of UHE cosmic rays. We also estimate the photon–neutrino decoupling temperature. In Section 2 we give the unparticle interactions with the SM fields and calculate the cross sections for the above processes. In Section 3 we give an estimate of the neutrino–photon decoupling temperature and the mean free path of neutrinos through intergalactic journey. This is followed by a discussion of our results in Section 4.

2. Neutrino–antineutrino annihilation

The effective interactions consistent with SM gauge symmetry for the vector and tensor unparticles with SM fields are given by

$$\frac{\kappa_1^{\mathcal{V}}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\bar{f}\gamma_\mu f\mathcal{O}_{\mathcal{U}}^\mu, \quad \text{and} \quad \frac{\kappa_1^{\mathcal{A}}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\bar{f}\gamma_\mu\gamma_5 f\mathcal{O}_{\mathcal{U}}^\mu \tag{6}$$

and for tensor unparticles the interactions are

$$\frac{-i}{4}\frac{\kappa_T}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}}\bar{f}(\gamma_\mu \overleftrightarrow{D}_\nu + \gamma_\nu \overleftrightarrow{D}_\mu)\psi_f\mathcal{O}_{\mathcal{U}}^{\mu\nu} \quad \text{and} \quad \frac{\kappa_T}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}}\mathcal{F}_{\mu\alpha}\mathcal{F}_\nu^\alpha\mathcal{O}_{\mathcal{U}}^{\mu\nu}, \tag{7}$$

where f stands for a SM fermion doublet or singlet, $\mathcal{F}_{\mu\nu}$ is electromagnetic field tensor and the dimensionless coupling constants κ_i's are related to the coupling constant $\mathcal{C}_{\mathcal{U}}$ and the mass scale $M_{\mathcal{U}}$ through

$$\frac{\kappa_1^{\mathcal{V},\mathcal{A}}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} = \mathcal{C}_{\mathcal{U}}^{\mathcal{V},\mathcal{A}}\frac{\Lambda_{\mathcal{U}}^{3-d_{\mathcal{U}}}}{M_{\mathcal{U}}^2} \quad \text{and} \quad \frac{\kappa_0^{\mathcal{T}}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} = \mathcal{C}_{\mathcal{U}}^{\mathcal{T}}\frac{\Lambda_{\mathcal{U}}^{2-d_{\mathcal{U}}}}{M_{\mathcal{U}}^2}. \tag{8}$$

The neutrinos being left handed the scalar operator does not couple to them and therefore we consider only the vector and tensor operators. The unparticle propagator for the vector and tensor fields are given by [10,16]

$$[\mathcal{A}_{\mathcal{F}}(P^2)]_{\mu\nu} = \frac{\mathcal{A}_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}\left(-P^2\right)^{d_{\mathcal{U}}-2}\pi_{\mu\nu}(P) \quad \text{where } \pi_{\mu\nu}(P) = -g^{\mu\nu} + \frac{P^\mu P^\nu}{P^2}, \tag{9}$$

$$[\mathcal{A}_{\mathcal{F}}(P^2)]_{\mu\nu,\rho\sigma} = \frac{\mathcal{A}_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}\left(-P^2\right)^{d_{\mathcal{U}}-2}T_{\mu\nu,\rho\sigma}(P),$$

$$\text{where } T_{\mu\nu,\rho\sigma}(P) = \frac{1}{2}\left[\pi_{\mu\rho}(P)\pi_{\nu\sigma}(P) + \pi_{\mu\sigma}(P)\pi_{\nu\rho}(P) - \frac{2}{3}\pi_{\mu\nu}(P)\pi_{\rho\sigma}(P)\right]. \tag{10}$$

They satisfy the conditions $P_\mu \pi^{\mu\nu}(P) = 0$ and $P_\mu T^{\mu\nu,\rho\sigma}(P) = 0$. Further the unparticle operator $\mathcal{O}_\mathcal{U}$ and $\mathcal{O}_\mathcal{U}^{\mu\nu}$ are taken to be Hermitian and transverse and the tensor unparticle operator is also traceless. $\mathcal{A}_{d_\mathcal{U}}$ is the normalization factor for the two point unparticle operator and is given by

$$\mathcal{A}_{d_\mathcal{U}} = \frac{16\pi^{5/2}}{(2\pi)^{2d_\mathcal{U}}} \frac{\Gamma(d_\mathcal{U} + \frac{1}{2})}{\Gamma(d_\mathcal{U} - 1)\Gamma(2d_\mathcal{U})}. \tag{11}$$

The spin averaged cross-section induced by the vector, axial vector and tensor unparticle operators for the process

$$\nu(p_1) + \bar{\nu}(p_2) \to \mathcal{U}, \tag{12}$$

are calculated to be

$$\sigma_{\text{av}}^{\mathcal{V},\mathcal{A}}(\nu\bar{\nu} \to \mathcal{U}) = \left|\kappa_1^{\mathcal{V},\mathcal{A}}\right|^2 \left(\frac{s}{\Lambda_\mathcal{U}^2}\right)^{d_\mathcal{U}-1} \mathcal{A}_{d_\mathcal{U}} \frac{1}{s}, \tag{13}$$

$$\sigma_{\text{av}}^{\mathcal{T}}(\nu\bar{\nu} \to \mathcal{U}) = \frac{1}{32\Lambda_\mathcal{U}^2} \left|\kappa^{\mathcal{T}}\right|^2 \left(\frac{s}{\Lambda_\mathcal{U}^2}\right)^{d_\mathcal{U}-1} \mathcal{A}_{d_\mathcal{U}}. \tag{14}$$

The scattering process

$$\nu(p_1) + \bar{\nu}(p_2) \to \gamma_1(k_1) + \gamma_2(k_2), \tag{15}$$

gets the contribution only from the tensor unparticle operator. The SM contribution to the above process has been given in Ref. [9], we can easily compute the total contribution to the spin averaged cross-section and we get

$$\sigma_{\text{av}}(\nu\bar{\nu} \to \gamma\gamma) = \frac{1}{20\pi}\left[\mathcal{A}_{\text{SM}}^2 s^3 + 2\mathcal{A}_{\text{SM}}\mathcal{A}_{\text{Unp}}\cos\bigl(\pi(d_\mathcal{U} - 2)\bigr)s^{d_\mathcal{U}+1} + \mathcal{A}_{\text{Unp}}^2 s^{2d_\mathcal{U}-1}\right], \tag{16}$$

where

$$\mathcal{A}_{\text{SM}} = \left[\frac{14.4 g_W^2 \alpha_{em}}{32\pi m_W^4}\right], \qquad \mathcal{A}_{\text{Unp}} = \left[\frac{|\kappa^{\mathcal{T}}|^2 \mathcal{Z}_{d_\mathcal{U}}}{4\Lambda_\mathcal{U}^{2d_\mathcal{U}}}\right] \quad \text{and} \quad \mathcal{Z}_{d_\mathcal{U}} = \frac{\mathcal{A}_{d_\mathcal{U}}}{2\sin(d_\mathcal{U}\pi)}. \tag{17}$$

The cross-section for

$$\nu(p_1) + \bar{\nu}(p_2) \to f(p_1') + \bar{f}(p_2'), \tag{18}$$

gets the contribution from both the vector and tensor unparticles operators and we get

$$\begin{aligned}
&\sigma_{\text{av}}(\nu\bar{\nu} \to f\bar{f}) = \frac{2G_F^2 s}{3\pi}\left|\mathcal{R}(s)\right|^2\left[\left(C_\mathcal{V}^{f^2} + C_\mathcal{A}^{f^2}\right) + 2\cos(\pi d_\mathcal{U} + \Phi)C_\mathcal{V}^f \mathcal{B}_\mathcal{U}^\mathcal{V} + \left(\mathcal{B}_\mathcal{U}^\mathcal{V}\right)^2 + \left(\mathcal{B}_\mathcal{U}^\mathcal{T}\right)^2\right],\\
&\quad\text{where}\quad \mathcal{B}_\mathcal{U}^\mathcal{V} = \left[\frac{|\kappa^\mathcal{V}|^2 \mathcal{Z}_{d_\mathcal{U}}}{2\sqrt{2}|\mathcal{R}(s)|}\right]\left(\frac{\Lambda^{-2}}{G_F}\right)\left(\frac{s}{\Lambda^2}\right)^{d_\mathcal{U}-2}, \qquad \Phi = \tan^{-1}\left[-\frac{m_Z\Gamma_Z}{s - m_Z^2}\right], \qquad \mathcal{R}(s) = m_Z^2\frac{(s - m_Z^2) - im_Z\Gamma_Z}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2},\\
&\qquad\qquad \mathcal{B}_\mathcal{U}^\mathcal{T} = \left[\frac{\sqrt{3}|\kappa^\mathcal{T}|^2 \mathcal{Z}_{d_\mathcal{U}}}{16\sqrt{5}|\mathcal{R}(s)|}\right]\left(\frac{\Lambda^{-2}}{G_F}\right)\left(\frac{s}{\Lambda^2}\right)^{d_\mathcal{U}-1}, \qquad C_\mathcal{V}^f = T_3^f - 2\mathcal{Q}_f\sin^2\theta_W, \quad \text{and} \quad C_\mathcal{A}^f = T_3^f.
\end{aligned} \tag{19}$$

In Eq. (19) the second term within the square bracket is the interference term involving the SM vector and axial current with the vector unparticle current. The interference term of the vector and the tensor contribution vanishes identically after angular integration.

For a neutrino of energy E_ν annihilating a relic neutrino of mass m_ν we thus get

$$\sigma_{\text{av}}^{\mathcal{V},\mathcal{A}}(\nu\bar{\nu} \to \mathcal{U}) \simeq 4\left|\kappa_1^{\mathcal{V},\mathcal{A}}\right|^2 \mathcal{A}_{d_\mathcal{U}} 10^{8-3d_\mathcal{U}}\left(2\frac{m_\nu}{1\text{ eV}}\frac{E_\nu}{10^{21}\text{ eV}}\right)^{d_\mathcal{U}-2}\left(\frac{\Lambda_\mathcal{U}}{1\text{ TeV}}\right)^{2-2d_\mathcal{U}} \text{pb}, \tag{20}$$

$$\sigma_{\text{av}}^{\mathcal{T}}(\nu\bar{\nu} \to \mathcal{U}) \simeq 12\left|\kappa_2^{\mathcal{T}}\right|^2 \mathcal{A}_{d_\mathcal{U}} 10^{2-3d_\mathcal{U}}\left(2\frac{m_\nu}{1\text{ eV}}\frac{E_\nu}{10^{21}\text{ eV}}\right)^{d_\mathcal{U}-1}\left(\frac{\Lambda_\mathcal{U}}{1\text{ TeV}}\right)^{-2d_\mathcal{U}} \text{pb}, \tag{21}$$

$$\begin{aligned}
\sigma_{\text{av}}(\nu\bar{\nu} \to \gamma\gamma) \simeq{}& 7.57 \times 10^{-5}\left(2\frac{m_\nu}{1\text{ eV}}\frac{E_\nu}{10^{21}\text{ eV}}\right)^3\left[1 + 4.5 \times 10^6\left|\kappa_2^\mathcal{T}\right|^2 \mathcal{Z}_{d_\mathcal{U}}\left(2\frac{m_\nu}{1\text{ eV}}\frac{E_\nu}{10^{21}\text{ eV}}\right)^{d_\mathcal{U}-2}\left(\frac{\Lambda_\mathcal{U}}{1\text{ TeV}}\right)^{-2d_\mathcal{U}}\right.\\
&\left. + 5.09 \times 10^{6(1-d_\mathcal{U})}\left|\kappa_2^\mathcal{T}\right|^4 \mathcal{Z}_{d_\mathcal{U}}{}^2\left(2\frac{m_\nu}{1\text{ eV}}\frac{E_\nu}{10^{21}\text{ eV}}\right)^{2d_\mathcal{U}-4}\left(\frac{\Lambda_\mathcal{U}}{1\text{ TeV}}\right)^{-4d_\mathcal{U}}\right] \text{pb}.
\end{aligned} \tag{22}$$

$$\begin{aligned}
\sigma_{\text{av}}(\nu\bar{\nu} \to f\bar{f}) \simeq{}& 1.124 \times 10^4\left(2\frac{m_\nu}{1\text{ eV}}\frac{E_\nu}{10^{21}\text{ eV}}\right)\left[\left(C_\mathcal{V}^{f^2} + C_\mathcal{A}^{f^2}\right)\left|\mathcal{D}(m_\nu, E_\nu)\right|^2\right.\\
& + 6.06 \times 10^{4-3d_\mathcal{U}} C_\mathcal{V}^f\left|\kappa^\mathcal{V}\right|^2 \mathcal{Z}_{d_\mathcal{U}}\left(2\frac{m_\nu}{1\text{ eV}}\frac{E_\nu}{10^{21}\text{ eV}}\right)^{d_\mathcal{U}-2}\left(\frac{\Lambda}{1\text{ TeV}}\right)^{2-2d_\mathcal{U}}\\
& \times \left|\mathcal{D}(m_\nu, E_\nu)\right|\cos\{d_\mathcal{U}\pi + \Theta\}
\end{aligned}$$

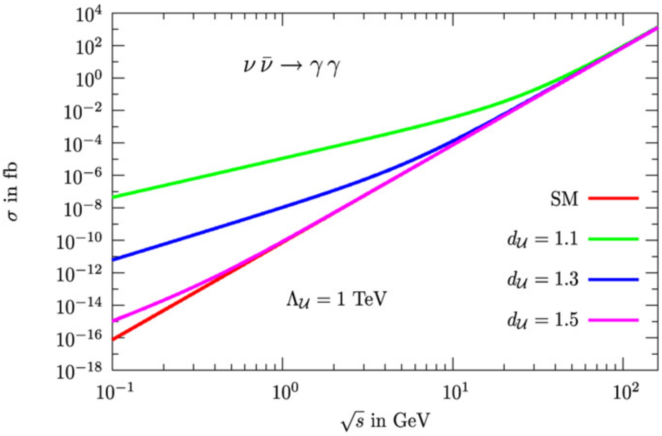

Fig. 1. SM + unparticle contribution to the total cross-section in fb for the photon pair production from neutrino pair annihilation via tensor unparticle for $\sqrt{s}$ varying from 0.1–160 GeV.

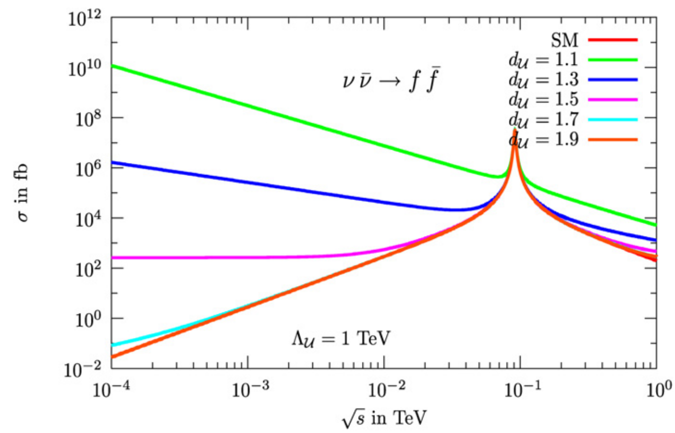

Fig. 2. SM + vector unparticle + tensor unparticle contribution to the total cross-section in fb for the charged fermion pair production from neutrino pair annihilation for $\sqrt{s}$ varying from 0.1 GeV–1 TeV.

Table 1
Mean free path of UHE ν due to annihilation with relic ν to produce vector unparticle

$d_{\mathcal{U}}$	1.1	1.3	1.5	1.7	1.9
$\lambda^{\mathcal{V}}$ in $\lvert\kappa^{\mathcal{V}}\rvert^{-2}$ Mpc	1.28×10^5	3.64×10^5	2.03×10^6	1.45 × 107	1.21×10^8

$$
\begin{aligned}
&+ 9.18 \times 10^{8-6d_{\mathcal{U}}} |\kappa^{\mathcal{V}}|^4 \mathcal{Z}^2_{d_{\mathcal{U}}} \left(2\frac{m_\nu}{1\ \text{eV}}\frac{E_\nu}{10^{21}\ \text{eV}}\right)^{2d_{\mathcal{U}}-4} \left(\frac{\Lambda}{1\ \text{TeV}}\right)^{4-4d_{\mathcal{U}}} \\
&+ 1.72 \times 10^{-9-6d_{\mathcal{U}}} |\kappa^{\mathcal{T}}|^4 \mathcal{Z}^2_{d_{\mathcal{U}}} \left(2\frac{m_\nu}{1\ \text{eV}}\frac{E_\nu}{10^{21}\ \text{eV}}\right)^{2d_{\mathcal{U}}-2} \left(\frac{\Lambda}{1\ \text{TeV}}\right)^{-2d_{\mathcal{U}}}\Bigg], \\
&\text{where } \mathcal{D}(m_\nu, E_\nu) = \left[1.2 \times 10^{-4}\left(2\frac{m_\nu}{1\ \text{eV}}\frac{E_\nu}{10^{21}\ \text{eV}}\right) + 0.027i\right]^{-1} \quad \text{and} \quad \Theta = \text{Arg}\big[\mathcal{D}(m_\nu, E_\nu)\big].
\end{aligned} \tag{23}
$$

The cross-section given in Eq. (22) and (23) for $\Lambda_{\mathcal{U}} = 1$ TeV are depicted in Figs. 1 and 2, respectively.

3. Neutrino mean free path and neutrino–photon decoupling temperature

From the cross-section expressions given above, we find that the mean free path of the neutrinos in their intergalactic journey is dominated by the annihilation of UHE neutrinos on relic neutrinos (relic density $n_\nu \simeq 56\ \text{cm}^{-3}$) through the production of unparticles. In the absence of any leptonic asymmetry, we have

$$
\begin{aligned}
\lambda^{\mathcal{V},\mathcal{A}}_{\nu\bar{\nu}\to\mathcal{U}} &= \big[\sigma^{\mathcal{V},\mathcal{A}}(\nu\bar{\nu} \to \mathcal{U}) n_\nu\big]^{-1} \\
&\simeq 1.44 \times 10^{3d_{\mathcal{U}}+1} \frac{|\kappa^{\mathcal{V},\mathcal{A}}|^{-2}}{\mathcal{A}_{d_{\mathcal{U}}}} \left[2\frac{m_\nu}{1\ \text{eV}}\frac{E_\nu}{10^{21}\ \text{eV}}\right]^{2-d_{\mathcal{U}}} \left[\frac{\Lambda_{\mathcal{U}}}{1\ \text{TeV}}\right]^{2d_{\mathcal{U}}-2}\ \text{Mp}
\end{aligned} \tag{24}
$$

and

$$
\lambda^{\mathcal{T}}_{\nu\bar{\nu}\to\mathcal{U}} \simeq 4.81 \times 10^{3d_{\mathcal{U}}+6} \frac{|\kappa^{\mathcal{T}}|^{-2}}{\mathcal{A}_{d_{\mathcal{U}}}} \left[2\frac{m_\nu}{1\ \text{eV}}\frac{E_\nu}{10^{21}\ \text{eV}}\right]^{1-d_{\mathcal{U}}} \left[\frac{\Lambda_{\mathcal{U}}}{1\ \text{TeV}}\right]^{2d_{\mathcal{U}}}\ \text{Mp}. \tag{25}
$$

The mean free path calculated from the production of the vector and/or axial vector unparticle increases with $d_{\mathcal{U}}$ and is much smaller than the corresponding mean free path for the tensor unparticle production. In Table 1 we present the mean free paths for various values of $d_{\mathcal{U}}$. The corresponding value in the SM, is given by $\lambda_{\nu\bar{\nu}\to Z^\star} \simeq 1.3 \times 10^{10}$ Mp. At resonance $\sqrt{s} = m_Z$, the Z exchange gives the largest cross-section with mean free path $\lambda_{\nu\bar{\nu}\to Z^\star} \simeq 0.35 \times 10^5$ Mp.

The temperature at which the reaction $\nu\bar{\nu} \to \gamma\gamma$ ceases to occur can be obtained from the reaction rate per unit volume, i.e.,

$$
\Gamma = \frac{1}{(2\pi)^6}\left[\prod_{i=1}^{2}\int \frac{d^3\vec{p}_i}{e^{E_i/T}+1}\right]\sigma_{\text{av.}}|\vec{v}|. \tag{26}
$$

Substituting the cross-sections from Eq. (22)

$$
\begin{aligned}
\Gamma &= \frac{1}{640\pi^5}\left[\frac{1024}{5}\mathcal{A}^2_{\text{SM}} T^{12}\mathcal{F}(5)^2 + 2\mathcal{A}_{\text{SM}}\mathcal{A}_{\text{Unp.}}\cos\big(\pi(d_{\mathcal{U}}-2)\big)\frac{4^{d_{\mathcal{U}}+3}}{d_{\mathcal{U}}+3}T^{2d_{\mathcal{U}}+8}\mathcal{F}(d_{\mathcal{U}+3})^2 + \frac{4^{2d_{\mathcal{U}}+1}}{2d_{\mathcal{U}}+1}\mathcal{A}^2_{\text{Unp.}} T^{4d_{\mathcal{U}}+4}\mathcal{F}(2d_{\mathcal{U}+1})^2\right] \\
&\text{where } \mathcal{F}(n) = \int \frac{x^n}{e^x+1}dx = \zeta(n+1)\Gamma(n+1)\left(1-\frac{1}{2^n}\right).
\end{aligned} \tag{27}
$$

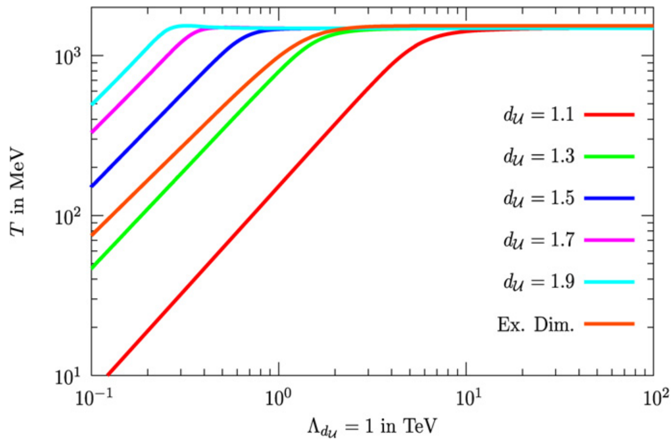

Fig. 3. Contours depicting the decoupling temperature T in MeV as a function of $\Lambda_{\mathcal{U}}$ for a fixed dimensionless coupling $|\kappa_i| = 1$ and various values of $d_{\mathcal{U}}$ varying between 1 and 2.

The interaction rate $\mathcal{R}$ is obtained by dividing the reaction rate Γ by the neutrino number density at temperature T namely

$$n_\nu = \frac{3\zeta(3)T^3}{4\pi^2}. \tag{28}$$

Thus the reaction rate R is given as

$$\mathcal{R}_{\nu\bar{\nu}\to\gamma\gamma} = 1.39 \times 10^{-23}\left(\frac{T}{1\ \text{MeV}}\right)^9 \otimes \Bigg[1 + 10^{18-12d_{\mathcal{U}}} 4^{d_{\mathcal{U}}} \frac{\cos(\pi(d_{\mathcal{U}}-2))}{d_{\mathcal{U}}+3} \left|\kappa^{\mathcal{T}}\right|^2 \mathcal{Z}_{d_{\mathcal{U}}} \mathcal{F}(d_{\mathcal{U}+3})^2 \left(\frac{T}{1\ \text{MeV}}\right)^{2d_{\mathcal{U}}-4} \left(\frac{\Lambda_{\mathcal{U}}}{1\ \text{TeV}}\right)^{-2d_{\mathcal{U}}}$$
$$+ 6.5 \times 10^{38-24d_{\mathcal{U}}} 4^{2d_{\mathcal{U}}} \left|\kappa^{\mathcal{T}}\right|^4 \frac{\mathcal{Z}^2_{d_{\mathcal{U}}}}{(2d_{\mathcal{U}}+1)} \mathcal{F}(2d_{\mathcal{U}+1})^2 \left(\frac{T}{1\ \text{MeV}}\right)^{4d_{\mathcal{U}}-8} \left(\frac{\Lambda_{\mathcal{U}}}{1\ \text{TeV}}\right)^{-4d_{\mathcal{U}}}\Bigg]\ \text{s}^{-1}. \tag{29}$$

Using the relation between the age of the universe and the temperature during this era namely

$$t_0 = 2.692\left[\frac{T}{1\ \text{MeV}}\right]^{-2}\ \text{s}, \tag{30}$$

the condition that at least one interaction takes place gives $\mathcal{R}_{\nu\bar{\nu}\to\gamma\gamma} \times t_0 = 1$. The solution of this equation gives the decoupling temperature and is shown in Fig. 3.

4. Results and discussion

In order to access the importance of the contribution of unparticles to ultra high energy neutrinos annihilating on cosmic neutrino background, we have plotted the average cross-sections $\sigma_{\text{av}}(\nu\bar{\nu} \to \gamma\gamma)$ and $\sigma_{\text{av}}(\nu\bar{\nu} \to f\bar{f})$ in Figs. 1 and 2. These cross-sections for the highest energy neutrinos have to be large in the vicinity of μ barns if the high energy photons and charged fermion pairs produced in these reactions which can then fragments into protons, have to account for the flux of the ultra high energy cosmic rays. From these figures we observe that the neutrino annihilation into fermion pairs can indeed be large and may even surpass the cross-section at Z resonance which has been considered in the literature [1] as a possible mechanism to explain UHE cosmic ray flux for 10^{20} eV events. For the highest energy neutrinos of energy $E_\nu \approx 10^{20}$–10^{21} eV and Super Kamiokande motivated mass $\simeq 10^{-2}$ eV, we find the cross-section $\sigma_{\text{av}}(\nu\bar{\nu} \to f\bar{f})$ to vary between 10^9 fb to 10 fb for the unparticle dimension $d_{\mathcal{U}}$ varying from 1.1 to 1.9, respectively. This cross cross-section is enough for at least one scattering to occur, i.e., it satisfies the condition $\sigma_{\text{av}}(\nu\bar{\nu} \to f\bar{f})n_\nu ct_0 = 1$ for $n_\nu ct_0 \simeq 10^{30}\ \text{cm}^{-2}$ where n_ν is the relic density ($56\ \text{cm}^{-3}$) and $t_0 = 13.5 \times 10^9$ years, the age of the universe. The cross-section for the production of a cascade of γ rays through $\sigma_{\text{av}}(\nu\bar{\nu} \to \gamma\gamma)$ is not enough to account for the UHE cosmic ray events. However, from Fig. 3 we see that this process can still give enough contribution to significantly lower the neutrino–photon decoupling temperature.

In conclusion, the present study shows that the unparticle physics can keep alive the hope of identifying UHE cosmic ray events with the highest energy neutrinos and the possibility of lowering the neutrino–photon decoupling temperature below the QCD phase transition albeit for low unparticle operator dimensions and coupling of the order one for $\Lambda_{\mathcal{U}} \approx 1$ TeV.

References

[1] T.J. Weiler, Astropart. Phys. 11 (1999) 303.
[2] G. Gelmini, A. Kusenko, Phys. Rev. Lett. 84 (2000) 1378.
[3] R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic, Astropart. Phys. 5 (1996) 81;
R. Gandhi, C. Quigg, M.H. Reno, I. Sarcevic, Phys. Rev. D 58 (1998) 093009.
[4] N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phys. Lett. B 429 (1998) 263;
N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phys. Rev. D 59 (1999) 086004;
I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, Phys. Lett. B 436 (1998) 257.
[5] S. Nussinov, R. Shrock, Phys. Rev. D 59 (1999) 105002;
P. Jain, D.W. McKay, S. Panda, J.P. Ralston, Phys. Lett. B 484 (2000) 267;
A. Goyal, A. Gupta, N. Mahajan, Phys. Rev. D 63 (2001) 043003.

[6] D.A. Dicus, W.W. Repko, Phys. Rev. D 48 (1993) 5106;
V.K. Cung, M. Yoshimura, Nuovo Cimento A 29 (1975) 557.
[7] C.N. Yang, Phys. Rev. 77 (1950) 242.
[8] A. Abbasabadi, A. Devoto, D.A. Dicus, W.W. Repko, Phys. Rev. D 59 (1999) 013012;
D.A. Dicus, C. Kao, W.W. Repko, Phys. Rev. D 59 (1999) 013005.
[9] D.A. Dicus, K. Kovner, W.W. Repko, Phys. Rev. D 62 (2000) 053013.
[10] H. Georgi, Phys. Rev. Lett. 98 (2007) 221601.
[11] H. Georgi, Phys. Lett. B 650 (2007) 275.
[12] T. Banks, A. Zaks, Nucl. Phys. B 196 (1982) 189.
[13] P.J. Fox, A. Rajaraman, Y. Shirman, Phys. Rev. D 76 (2007) 075004.
[14] M.J. Strassler, hep-ph/0801.0629.
[15] B. Grinstein, K. Intriligator, I.Z. Rothstein, hep-ph/0801.1140.
[16] K. Cheung, W.Y. Keung, T.C. Yuan, Phys. Rev. D 73 (2007) 075015.